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ABSTRACT

A conceptual study has demonstrated the technical possibility of replacing the RAVEN radio batteries with a solid polymer electrolyte fuel cell. The fuel cell would operate on air and stored hydrogen released from a metal hydride. The study revealed that the fuel cell power source offered logistical benefits over nickel cadmium batteries and potential cost savings over lithium sulphur dioxide batteries. The study suggests that methods of chemically generating hydrogen and oxygen should be investigated as they may provide significant increased power and energy density for such fuel cell power systems.

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Conceptual Study on Replacing the Raven Back Pack Radio Batteries with a Solid Polymer Fuel Cell

Executive Summary

A study has been undertaken into the feasibility of replacing the Raven back pack radio batteries with a conceptual solid polymer electrolyte fuel cell (SPEFC). The results of the study were:-

- It would be possible to build a SPEFC using metal hydride storage technology to replace the existing nickel cadmium and lithium sulphur dioxide batteries.
- The fuel cell system would be about the same size of the 4 Ah NiCd battery but would supply twice the energy storage for about the same mass of battery.
- The SPEFC design could provide the same energy storage as the $LiSO_2$ battery but with a weight penalty of 2.75 kg over the $LiSO_2$ but only a weight penalty of 0.54 kg over the NiCd battery whilst providing 3 times the energy of the NiCd.
- The SPEFC did provide significant benefits for patrol logistics when compared to the NiCd battery whilst also providing a 120 cc of potable water each day.
- The SPEFC system was more complex than a battery but existing technology would be able to provide a highly reliable system.
- The study revealed that the largest weight contribution was from the hydride storage and that alternate hydrogen storage techniques such as sodium boron hydride and calcium hydride should be investigated.
- The study also suggested that the successful development of a SPEFC system could offer cost savings to the ADF.
- Further investigations should also consider the possibility of using a chemical store of oxygen rather than using air. Such operation would likely improve power density and it would remove the need for an air intake that needs protection against dust and water ingestion.

Contents

1. Introduction

This report presents a conceptual study on replacing the nickel cadmium (NiCd) and lithium sulphur dioxide ($LiSO_2$) batteries used in the Raven radio of the Australian Defence Force (ADF) with a solid polymer electrolyte fuel cell (SPEFC) system. The current batteries are expensive and divided into essentially two functions. The NiCd batteries are secondary batteries with approximately twice the mass and nominally half the electrical capacity of the $LiSO_2$ batteries. They are used for short patrols and training and in comparison to the $LiSO_2$, they are very cost effective because of their recharge capability. However, for long patrols and wartime situations the $LiSO_2$ would preferably be used due to their superior performance and the less demanding load carrying requirement for the soldiers. Unfortunately the $LiSO_2$ is a primary battery which means that once discharged it has to be disposed of. SPEFC's offer the possibility of a single source of power for the Raven radio that would provide a quick recharge capability with an energy storage equal to or greater than the $LiSO_2$ with a commensurate low operating cost.

2. Fuel Cell Technology

A fuel cell is an electrochemical device similar to a battery in that the combination of chemicals will produce direct current (DC) power. In a fuel cell the oxidant and the fuel are stored and supplied to the electrodes of the fuel cell externally whereas a battery consumes chemicals stored internally. Subsequently, fuel cells can supply electric power indefinitely provided the fuel and oxidant supplies are maintained. Typical open circuit cell voltages are 1-2 Volts depending on the type of fuel cell. Higher voltages are obtained by stacking multiples of the cells together in series and higher currents are achieved by increasing the cross-sectional area of the cell or connecting them in parallel.

Most fuel cells use oxygen or air as the oxidant and hydrogen is generally the fuel. Fuel cells can achieve quite high efficiencies in the production of DC power as the process is not limited by the Carnot cycle. Subsequently, power generation efficiencies between 50% and 70% are possible and system efficiencies can be greater than 80% if waste heat is utilised [1]. In addition, the power generation within the cell is silent like a battery.

There are a number of fuel cell technologies existing today. The most prominent forms are phosphoric acid fuel cells (PAFC), solid polymer electrolyte (SPEFC), alkaline (AFC) and solid oxide (SOFC), all of which are in various states of development. This report deals with SPEFC's which operate from room temperature to 90°C. SPEFC's use a solid polymer electrolyte membrane which has a porous electrical conductor (commonly graphite paper or cloth) bonded to each surface. A catalyst (commonly Platinum) is interposed between the membrane and the conductor. Hydrogen gas molecules entering the cell are ionised at catalyst sites into two hydrogen ions. The

electrons stripped from the hydrogen molecule flow through the load to the anode side of the cell. The hydrogen ions diffuse through the electrolyte membrane to the anode where they interact with oxygen molecules at catalyst sites to form pure water (Fig 1). The normal operating voltage of a SPEFC is typically about 0.7 volt (~1 V open circuit) reducing down to a practical minimum of 0.5 volt. The half reaction and full reaction equations are shown below.

Anode: $H_2 \rightarrow 2H^+ + 2e^-$
Cathode: $^1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Full reaction: $H_2 + ^1/2O_2 \rightarrow H_2O$

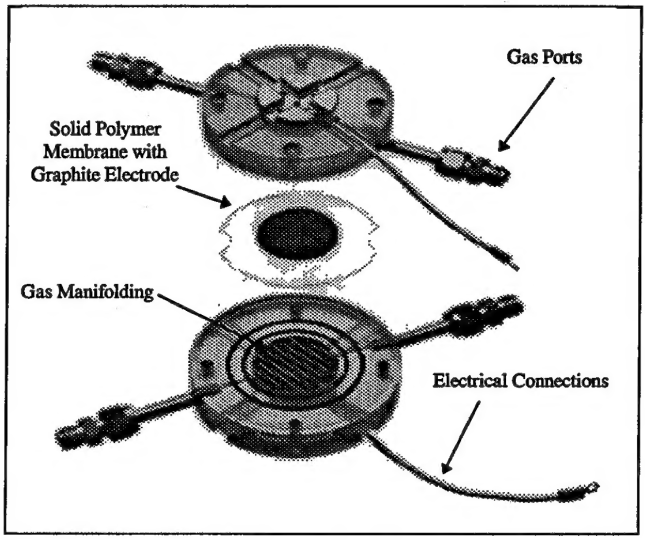

Figure 1. Picture of an Experimental Single Cell Solid Polymer Electrolyte Fuel Cell used at AMRL.

3. Conceptual Design of the Fuel Cell System

In designing a conceptual fuel cell system to replace the Raven batteries the following criteria were set:-

- Electrical capacity to be at least equal to the $LiSO_2$ batteries, ie. 8 Ah.
- Size to be no greater than the largest of the NiCd batteries.
- Mass to be no greater than the largest of the NiCd batteries, ie. 3.7 kg.

Figure 2 shows a diagram of the conceptual SPEFC system. The system uses stored hydrogen fuel and air as the oxidant. A small DC electric fan blows air through the fuel cell and H_2 is stored as a metal hydride in a stainless steel cylinder. The air must flow through the fuel cell stack otherwise there would be a build up of nitrogen within the stack as the oxygen is consumed. The H_2 flow to the stack is "dead-ended" meaning that the H_2 does not exit the stack. It is all consumed in situ and replaced by maintaining a constant pressure in the stack from a pressurised source of H_2.

A metal hydride was chosen as the means of storage because of its simplicity, safety and higher storage density[1] in comparison to more traditional methods such as compressed H_2 gas or liquid H_2. In addition, liquid H_2 would be a logistical nightmare due to its cryogenic nature. In the case of a bullet piercing a hydride bottle there would inevitably be a loud noise and hydrogen gas[2] contained within the bottle would vent under high pressure from the bottle. Testing with high velocity bullets has shown[10] that it is not possible for an explosion to occur due to the sponge nature of the hydride.

To desorb the H_2 stored within the metal hydride, it is heated by the ambient air and waste heat from the fuel cell. The H_2, which is very pure from a hydride, and the oxygen within the air are consumed within the fuel cell stack where DC power is generated and pure water is produced. Some of the product water is wicked into the stack to humidify the incoming gases. Because the fuel cell voltage varies according to the load drawn from the fuel cell, the electrical output from the stack is converted by a compact DC-DC converter to a fixed output voltage suitable for the radio.

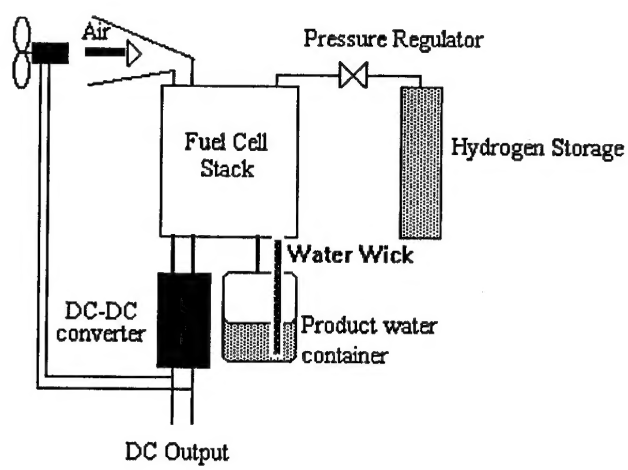

Figure 2. System diagram for conceptual SPEFC to replace Raven batteries.

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[1] A metal hydride will typically store H_2 at a greater density than liquid H_2

[2] Hydrogen gas will exist in equilibrium with the hydrogen gas dissolved within the metal hydride. The amount of hydrogen gas will depend on free volume and the thermodynamics of the metal hydride.

In designing and costing the conceptual unit, existing commercial equipment was chosen wherever possible and retail prices were used. The fuel cell stack itself was not available for purchase off the shelf. Accordingly, the design was based on technology currently being used in larger commercial units. The performance parameters were also obtained from existing fuel cell systems. Costing of components used within the fuel cell stack used retail prices.

4. Design Features and Calculations

The following sections describe the specifications and calculations used in a spreadsheet calculation for the conceptual model of the fuel cell system. The spread sheet is detailed in the Appendix.

4.1 Current Battery Specifications

The existing batteries used for the Raven radio and ancillary equipment consists of NiCd batteries that are rechargeable and a $LiSO_2$ battery that offers double the capacity of the NiCd but is not rechargeable. The batteries considered in this report concern the larger of the NiCd and the $LiSO_2$ battery. The mechanical and the electrical details are listed below.

NiCd capacity is	118	Wh
$LiSO_2$ capacity is	238	Wh

Note: $LiSO_2$ battery is approximately half the size of NiCd.

	NiCd	**$LiSO_2$**
Nominal battery capacity	118 Wh	236 Wh
Normal mission life on patrol[3]	12 hours	36 hours

Note: Although the NiCd battery is half the nominal capacity of the $LiSO_2$ it only produces one third of the normal mission life according to reference [2]. No explanation for this reduction in mission life was given. NiCd batteries do suffer from self discharge [3] but this would not be a probable cause for such a difference in mission life. Subsequently, the actual useable capacity of the NiCd when used in the Raven radio is one third of the $LiSO_2$ battery, viz 78.7 Wh. This was the capacity used in comparison with the conceptual fuel cell system.

Max required battery power is 141.6 Watts
Maximum current drain on either battery is 4.8 Amps

[3] Based on continuous use with a 1:9 transmit/receive ratio [4]

Figure 3 displays a photo of the NiCd battery and Table 1 lists the specifications of the 4 Ah NiCd and 8 Ah $LiSO_2$ batteries in the ADF inventory for the Raven backpack radio.

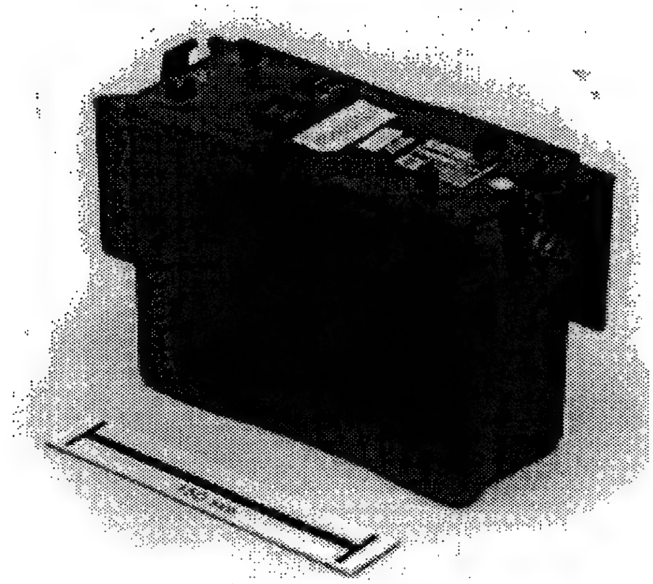

Figure 3. Photograph of the Raven 4 Ah NiCd battery.

Maximum Voltage of either battery is 29.5 volts, however an allowance is made in the radio to operate up to 32 Volts when in the receive state (light load) for the benefit of the higher voltage from the $LiSO_2$ battery. Sustained current drain on the batteries is typically 100-200 mA with a transmit current (averaged over a period of a few seconds) of 1.5-2.5 A with peaks up to 4.8 A required for Morse code or single sideband operation [4].

Table 1. Parameters of the Raven Back Pack Batteries [4].

	Nominal capacity (Ah)	Mass (kg)	Size (l*h*w) (mm)	Operating Voltage (DC)	Number of Recharge Cycles
NiCd	4	3.7	216*82*146	18-29.5	200 [2]
$LiSO_2$	8	1.5	218*82.5*91	18-32	0

4.2 Fuel Cell Specifications

A baseline on performance characteristics for the model was established from the performance of the AMRL fuel cell stack manufactured by Energy Partners (EP). This fuel cell stack requires 60 l/min of H_2 flow at 5 kW when operating with pure O_2 and

H_2. However, the EP stack uses the Nafion 117 membrane manufactured by Du Pont which is a relatively old membrane technology. A higher performing membrane is NE105 5L, also manufactured by the Du Pont chemical company. With this membrane there would be a 75% increase in power with the same amount of gas. It was assumed for this report that the NE 105 5L membrane would be used. However, only 50% more power from the fuel cell was assumed, meaning the required H_2 flow was 8 l/min/kW. However, any SPEFC replacement for the Raven battery would operate off air, not pure oxygen, and unfortunately the fuel cell performance is reduced due to the lower concentration of O_2. The EP stack produces approximately half the power with air operation so a factor of 60% reduction with air as the oxidant was used in this report. This meant the H_2 flow required increased to 20 l/min/kW.

Table 2. Power and Current Densities at typical Operating Cell Voltages.

Cell Voltage Volts	Current Density A/cm2	Power Density W/cm2
0.5	0.8	0.4
0.6	0.6	0.36
0.7	0.25	0.175

The operating voltage of the fuel cell will decrease as the power output is increased. Typical operating voltages for each cell in a stack are between 0.5 and 0.7 Volts. Known SPEFC performance on Air/ H_2 is given in Table 2 for operation at 1/1 atm pressure. Because the voltage must be at a nominal 29.5 volts for the radio, the output of the fuel cell would be converted by a DC-DC converter to the required voltage. These converters typically have an 85% efficiency [5] but an efficiency of 80% was used for the report. This meant the fuel cell stack would have to produce a maximum power output of 177 W.

It should be noted that the fuel cell will deliver at the very least the full electrical capacity stored in the H_2. In fact, with a 1:9 transmit:receive ratio the fuel cell system will deliver more than the nominal energy because at low loads (receive mode) it will be operating at a higher efficiency, possibly as much as 10% higher[4].

4.3 Conceptual Layout for Fuel Cell System

Figure 4 shows the conceptual layout of the fuel cell system to replace the Raven battery. The size was based on the larger of the NiCd batteries. The largest of the system components that also has the greatest mass, is the stainless steel (SS) bottle containing the metal hydride. This bottle has to be robust to withstand the internal pressures generated as the H_2 is desorbed from the metal matrix. It must also be

[4] A fuel cell stack manufactured by Siemens of Germany will operate on pure O_2 at 59% efficiency at rated load and 69% at 20% load[1]. This fuel cell uses the old technology membrane Nafion 117.

thermally conducting to absorb heat from the atmosphere and the fuel cell. The bottle is attached by a double-ended shut off connector to a compact fixed-pressure regulator. This item would need to be designed for the system as existing units available are quite large and massive. Discussions with a regulator designer [6] suggest that it would be possible to reduce the regulator size down to a size not much bigger than a match box. The diameter of the regulator was set at 50 mm for this report and is generally based on a commercial unit [7].

Items not able to be purchased off the shelves include:-

- The gas bottle and the associated connector: Both would use existing technology.
- The fuel cell: It would use the current state of the art technology involving printed membranes and moulded graphite plates.
- Encapsulated DC-DC converter: This would use existing technology but specifically designed for the unit. Efficiency would be between 85-90% based on current technology [5].
- The case: It would be based on the existing casing of the batteries.
- Valves for stopping water ingression into the unit: The air manifold for the fuel cell would need to be designed to stop any ingestion of water into the fuel cell.

4.4 Hydrogen Storage Calculations

The hydride/gas bottle was designed with walls 3 mm thick with a potential maximum diameter no greater than the external dimensions of the case (82 mm). With the maximum diameter of 82 mm, the bottle had maximum pressure rating[5] of 16 MPa (2268 Psi). Assuming spherical end caps, this gave a maximum internal volume of 1.56 litres.

Before the H_2 storage volume of the bottle could be calculated, a number of design details needed to be addressed. These were:-

- One third of the bottle volume is occupied by gaseous hydrogen and two thirds by the metal hydride because the metal hydride is required to be in a porous form to ease absorption and desorption. This means there would always be some gaseous hydrogen immediately available for use in the fuel cell.
- In the remaining two thirds of the bottle's volume that contains the metal hydride, only two thirds of that volume will actually be occupied by the hydride due to heat conductors and packaging of the hydride to allow for expansion[6].

The DC-DC converter will transform the variable fuel cell DC output[7] to the desired 29.5 V with a maximum output current of 4.8 A. Such converters would also have

[5] Using thin wall pressure vessel calculations based on tensile strength for stainless steel of 198 MPa.
[6] Typical expansion of the metal matrix with the formation of the hydride is approximately 25%.

short circuit current and thermal overload protection. They can also have very good reliability having mean-time-between-failure (MTBF) as high as 500,000 to 1,000,000 hrs[5].

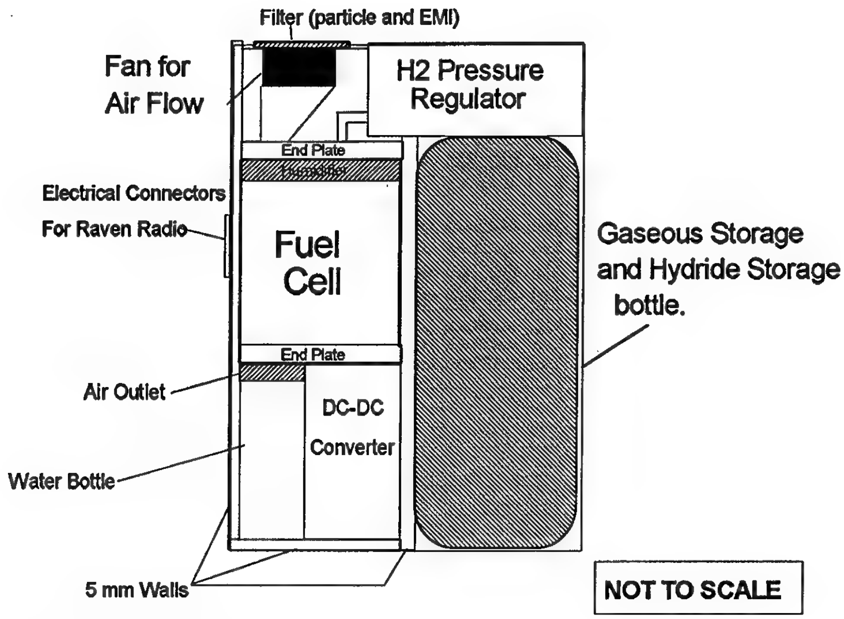

Figure 4. Conceptual Layout of Fuel Cell System.

4.5 Hydride Storage

The hydride, $FeTiH_2$ was chosen because amongst existing hydrides it stores a relatively high weight percentage of H_2 within it. It also desorbs at room temperature and is readily available at a reasonable price. It will store the equivalent of 1.3 times liquid H_2 in a given volume[8]. Ninety percent of this factor was used in the report.

The volume of gaseous H_2 stored was calculated from 60% of the maximum pressure rating for the bottle and one third of the bottle's volume.

4.6 Gas Consumption and Energy Stored in Cylinder

To obtain the required output power of 177 W the fuel cell stack will need 3.54 litre/min of H_2 which when divided into the total H_2 storage, will give the total

[7] Fuel cell voltages fall as output power increases.
[8] Liquid H_2 is 845 times denser than gaseous H_2 at STP.

operating time at maximum power and subsequently the electrical capacity of the fuel cell system.

4.7 Fuel Cell Size Calculation

The maximum width of the fuel cell was determined from the remaining space in the casing after walls and the bottle diameter had been deducted. Similarly, the maximum height of the fuel cell was the height of the casing minus two walls. The active cross-sectional area of the membrane in the fuel cell was 10 mm thinner than the width of the fuel cell and 20 mm shorter than the height. Twenty millimetres was used in the height calculation to allow for internal gas manifolding within the fuel cell stack. This internal manifolding of the gases is typical of modern commercial fuel cells and the 20 mm spacing would also allow for bolts needed to clamp the cells together.

Table 3 shows the number of cell plates and humidifier plates were needed for the operating voltages of 0.5, 0.6 and 0.7 V.

Table 3. Numbers of Cell and Humidifier Plates in Stack.

Cell Operating Voltage	Number of Cell Plates[9]	No. of Humidifier Plates
0.5	11	4
0.6	12	5
0.7	23	8

The incoming gases must be humidified and as a rule of thumb, the oxygen side of the cells requires one fifth the total number of fuel cells for humidification and the H_2 needs one seventh. These numbers were rounded up to the nearest integral. The design used moulded graphite cell plates[10] 2.5 mm thick with stiff end plates 4 mm thick.

4.8 DC-DC Converter

A review of DC-DC converter technology shows that encapsulated converters have long MTBFs and high transformed energy density. Figures quoted by Powerbox [5] are 36 Watts /cubic inch which translates to 2.08W/cc. This figure was used to calculate the volume needed to fit the DC-DC converter. The DC-DC converter was

[9] Rounded up to the nearest whole number.

[10] The Energy Partners fuel cell uses moulded graphite cell plates. Such plates can be made cheaply and efficiently.

mounted next to the hydride bottle so its waste heat could be used to desorb the H_2. The DC-DC regulator would also have an output for running the small quiet fan.

4.9 Water Balance Calculations

As mentioned previously, the fuel cell needs water for humidification. This water would need to be carried if the fuel cell stack does not produce enough for its own use.

Using the following equation[11] for the partial pressure (Atm) of water in 100% saturated gas [8] it is possible to determine the water requirement for humidification of the cells.

$$P(sat)=(377.4016-2.3147*T+0.003744*T^2)/14.696 \qquad (1)$$

Using T = 60°C (333.15°K) a P(sat) of 0.20 Atm (19,850 Pa) is obtained. This is the partial pressure of the moisture in the 100% saturated gas. From Ballard results[8], the H_2 stream must be 50% saturated at the operating temperature and the air must be 100% saturated at the same temperature.

5. Results and Discussion

By adjusting the size of the hydride bottle diameter it was possible to obtain a number of mass and capacity combinations. It did not prove feasible to fully satisfy the design criteria. To obtain a SPEFC system with the same capacity as the $LiSO_2$ battery required an extra 0.57 kg more mass than the NiCd battery. However, for the same mass as the NiCd battery, 110% extra electrical capacity could be carried in the SPEFC system. To obtain an electrical capacity the same as the $LiSO_2$ battery, the SPEFC system needed to be 0.57 kg heavier than the NiCd battery (2.77 kg heavier than the $LiSO_2$ bat). Table 4 lists a range of results[12].

[11] This equation appears to only produce reliable answers around 60°C.

[12] One feature not considered in the energy storage of the hydride system was the transmit to receive ratio of 1:9. In a low power receive mode the efficiency of the fuel cell may be 10% or more higher due to the lower power drain. Subsequently there would be a significant increase in the electrical capacity of the system if the 1:9 ratio was considered. In addition, the fuel cell system should be able to supply full power continuously without affecting the rated capacity of the system given in table 4.

Table 4. Range of results from varying hydride bottle diameter.

Hydride Bottle Diameter (mm)	Factor on NiCd Battery	Factor on $LiSO_2$ battery Capacity	Total System Mass (kg)	Mass of Hydride Bottle (kg)
41	2.1	0.7	3.70	1.22
50	3.0	1.0	4.27	2.79
65	4.5	1.5	5.27	3.81
82	6.0	2.0	6.37	4.89

Although the system could not satisfy all the design criteria, an analysis of the total electrical capacity that must be carried on patrol did show some advantages with an SPEFC system. Table 5 shows the total system masses (batteries, fuel cell system & spare hydride bottles) that would have to be carried on patrols up to 5 days long[13]. Figure 5 shows the results graphically.

Table 5. Total system masses with SPEFC, NiCd and $LiSO_2$ batteries.

Days On Patrol	Total SPEFC system Mass (kg)			Excess	Battery Mass	
	Bottle dia=41mm	Bottle dia=50mm	Bottle dia=65mm	H_2O (kg)or (l)	NiCd kg	$LiSO_2$ kg
1	3.70	4.27	5.27	0.12	7.40	1.50
2	4.92	7.06	5.27	0.24	14.80	3.00
3	6.14	7.06	9.08	0.35	22.20	4.50
4	7.36	9.85	9.08	0.47	29.60	6.00
5	8.58	12.64	12.89	0.59	37.00	7.50

All the SPEFC systems were much lighter to carry than the NiCd batteries making as much as 28 kg difference over a 5 day patrol (Table 5). The results (Appendix) also show that the H_2O production is 1.7 times the water requirement for humidification purposes. Consequently, all the SPEFC systems will produce about 120 cc (gms) of potable water per day. However, Fig 5 clearly shows that none of the SPEFC systems using current hydride storage could equal the $LiSO_2$ battery for energy density.

[13] Remember, on average, one $LiSO_2$ and three NiCd batteries must be carried for 36 hours on patrol. This assumes continuous use with a 1:9 receive:transmit ratio.

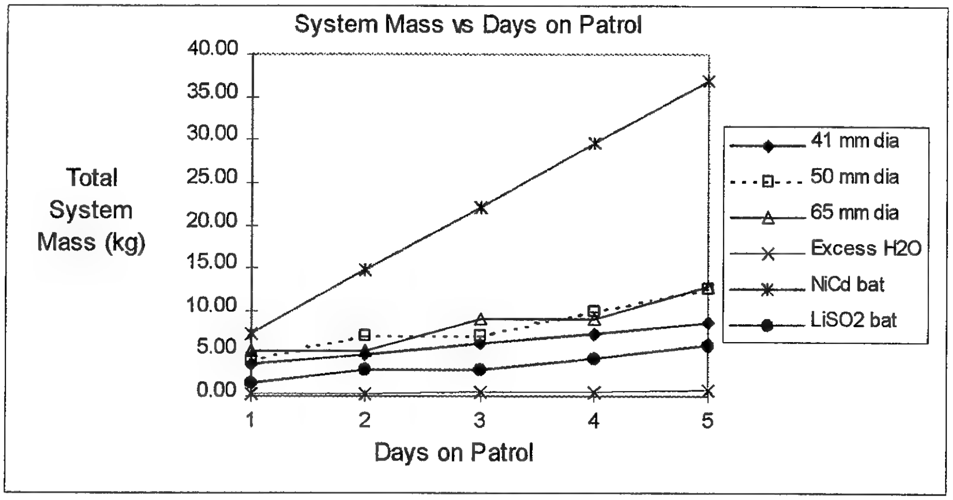

Figure 5. Graph of total system masses versus days on patrol[14].

The costing of the SPEFC system was estimated to be approximately $2,300 per unit complete with one hydride bottle (see Appendix). Each additional hydride bottle would cost about $430. However it should be noted that these estimates are based on retail prices and mass production prices would be expected to be significantly lower. However, these prices serve as a first order approximation. Using these cost estimates and costs of the $LiSO_2$ and NiCd batteries [4] a 5 year costing of the different power systems was performed to yield some insight into the cost considerations (Fig 6).

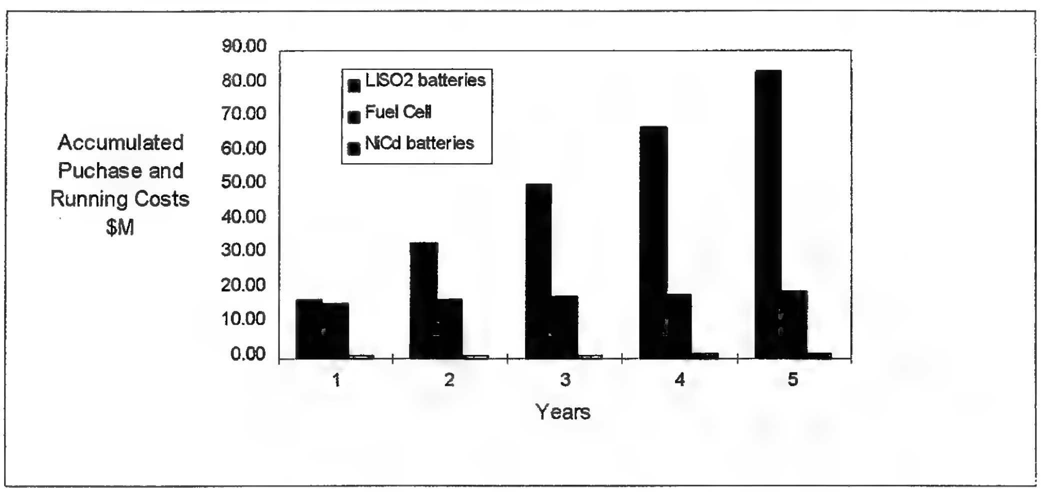

Figure 6. Accumulated running costs of the $LiSO_2$, NiCd batteries and the fuel cell. Running time was 800 hours/radio/yr and inflation factors were not considered.

[14] The non-linearity of the SPEFC graphs is due to rounding up on the number of hydride bottles that would need to be carried to meet the daily electrical requirements.

The costing (Fig 6) clearly shows that the use of the NiCd batteries provides significant savings over both the fuel cell and the $LiSO_2$ batteries. However, soldiers on patrol will suffer a large mass penalty using NiCd batteries compared to the other systems (Fig 5). For long patrols where the $LiSO_2$ offers excellent energy density the operational cost can be very high compared to the slightly heavier SPEFC units where costing is essentially tied to the initial purchase of the units. H_2 consumption costs for the SPEFC system would be under $800,000/yr and the SPEFC systems would be expected to have long operational lives[15]. Nevertheless, analysis of the 5 year costing of the $LiSO_2$ battery showed that the SPEFC system would be dearer than the $LiSO_2$ battery if the $LiSO_2$ batteries were required for less than 150 hours/radio/yr.

One distinct disadvantage with the SPEFC in comparison to a battery system is the need to ensure access to air for operation. Accordingly, any SPEFC system replacement for the Raven battery would require protection against water ingestion. This could be accomplished with a lightweight conformal snorkel along the side of the radio to allow continuous operation when traversing through water.

6. Conclusions

The study has shown that it would be possible to build a SPEFC system using metal hydride storage to replace the NiCd and $LiSO_2$ batteries. Using conservative estimates of power density and storage capacity the results show that a SPEFC system using hydride storage would be the same size as the 4 Ah NiCd battery and would be able to supply more than twice the useable electrical energy as the NiCd for the same mass. However, it would not be cost effective to replace the NiCd batteries.

At a weight penalty of 2.75 kg over the $LiSO_2$ and 0.57 kg over the NiCd, the SPEFC system could provide the same energy as the $LiSO_2$ battery or 3 times the NiCd. Nevertheless, in all the configurations considered, the SPEFC system using hydride storage could not equal the $LiSO_2$ battery energy density. However, The SPEFC did provide a significant weight advantage over the NiCd battery when multiple day patrols were considered. In addition, the system produced water excess to its requirements providing up to 120 cc of potable water each day. The greatest contribution to the mass of the SPEFC system was the hydride tank which highlights the need for a better chemical storage method for H_2.

[15] Small experimental SPEFC's operating with Nafion 117 have operated for 20,000 hours with individual cell voltages only dropping 0.1 V. Life times studies on recent higher performing membranes have not yet been published.

A SPEFC system will be more complex than a simple battery and accordingly reliability of all associated components, eg. fuel cell, fan, DC-DC converter, electronic control, etc will have to be very high. Other factors that would also have to be investigated would be operating temperature range, system thermodynamics, operation in different orientations, ease of maintenance, ruggedness, etc. Nevertheless, this conceptual study has revealed some insight into the potential to replace traditional battery systems with a solid polymer fuel cell system. The results suggests that alternative chemical methods of storing hydrogen such as sodium boron hydride ($NaBH_4$) and calcium hydride (CaH_2) should be investigated. Such chemicals will offer a much higher Wh/kg and Wh/cc than hydrides [9] and they may offer systems equal to or better than the $LiSO_2$ battery with the potential for considerable long term cost savings to the ADF. Further work should also investigate the chemical generation of oxygen rather than using air as the oxidant. Pure oxygen fed to the fuel cell would significantly improve the power density of the fuel cell stack.

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10. Annex A to RANSLO letter 384/5/79 (17th Mar89) Attached to Report by P.D. Briggs Capt RAN, (April 1989). Fuel Cell Demonstration - Kiel 14 Mar 89.

8. Addendum

Recent developments[16] in PEM fuel cells operating on atmospheric pressure air have demonstrated fuel cell membrane power density increases of 42%- 84% (@ 0.5-0.7 volts) greater than those used in this report. Commensurate with such increased power density is increased power generation efficiency (~43%-59%). Applying this technology to the conceptual design would produce an overall smaller and lighter power unit due to reduced sizes and masses of the fuel cell stack, metal hydride storage and possibly the fan. It may even be possible to remove the DC-DC converter due to potentially less voltage variation from the fuel cell stack thereby producing a much simpler design with higher reliability, lower logistical needs and potentially lower cost.

[16] Appleby, J.A. (1994) Fuel Cells for Traction Applications - An Overview. Proc Fuel Cells for Traction Applications, the Royal Swedish Academy of Engineering Science, (IVA), Stockholm, Sweden, Feb 8, 1994.

Appendix

Preliminary calculations for a conceptual fuel replacement for Raven batteries.									
file:battery.xls									
		length	*width*	*height*					
NiCd battery size is		0.218	0.146	0.082	metres				
NiCd capacity is		79	Wh [2]						
LiSO2 capacity is		238	Wh [2]		Note:LiSO2 battery is approx half size of NiCd				
Maximum Voltage of either battery is				29.5	volts	Max battery Power is		141.6	Watts
Maximum current drain on either battery is				4.8	Amps				
Normal use is one LiSO2 or 2 NiCd per 36 hrs on Patrol [2]									
H2 Gas Requirement Cal's									
Considering EP fuel cell figures we have 60 l/min at					5	kW on O2 and H2.			
Considering NE105 5L membrane we would get at 75% more power for the same amount of gas.									
We shall only consider			50%	more power with NE105 5L					
NE105 5L									
Power	*Gas Flow*	*O2/H2*					*Air/H2*		
Output kW	*l/min*	*kW/l/min*		*On Air, performance is*			*kW/l/min*		
7.5	60	0.125		60%	*less.*		0.05	*H2 consumption*	
Known performance at ambient pressure for Air/H2.									
Air/H2 at 1/1 atm pressure									
Cell	*Current*	*Power*							
Voltage	*Density*	*Density*							
Volts	*A/cm2*	*W/cm2*							
0.5	0.8	0.4							
0.6	0.6	0.36							
0.7	0.25	0.175							
DC- DC converter efficiency is nominally greater than 85%. We will assume					80%				
This means we need the fuel cell output to be					0.177	kW			

HYDROGEN STORAGE CALCULATIONS						
Hydride/gas bottle will have walls				0.003	metre thick.	
Pressure rating based on tensile strength for Stainless Steel of					198	MPa
is calculated from thin wall pressure rating formula. pressure=young's mod*2*wall thickness/internal dia						
Outside diameter =		0.041	metres	Internal Diameter =	0.035	metres
Max pressure =		34	MPa	OR	4924	PSI
Internal volume of bottle assuming spherical ends =				0.49	litres	
Assumptions						
One third the bottle volume is occupied by gaseous hydrogen and half by the metal hydride.						
Of the two thirds volume for hydride storage only 2/3 of that vol will actually be occupied by the hydride due to heat conductors and packaging of the hydride to allow for expansion.						
HYDRIDE STORAGE						
Hydride:	FeTi	Equivalent Liquid Hydrogen storage factor:			1.3	90% of this was used.
Liquid hydrogen is		845	denser than gaseous hydrogen.			
Volume of Hydride =		0.22	litres			
Volume of hydrogen stored =			215.2	litres (@ STP)		
GASEOUS STORAGE						
Vol of STP Gaseous H2 stored under pressure in half the bottle =					32.82	litres
(Only 60% of Maximum bottle pressure was used.)						
TOTAL HYDROGEN STORAGE =				248.02	Litres (@ STP)	
Gas consumption of Unit & Energy Stored in Cylinder						
To obtain output Power we need				3.54	litre/min of H2	
Operational time for radio =				70.06	minutes	
kWh for the fuel cell system =				165.35	kWh	
This is a factor of		2.09	times the NiCd battery capacity.			
This is a factor of		0.69	times the LiSO2 battery capacity.			

FUEL CELL SIZE CALCULATION										
Maximum width of the fuel cell will be equal to the width of the case -2*walls- dia of the bottle										
Max Width =		0.095	metres							
Max Height =		0.072	metres							
Allowing	0.005	m wide edges on 2 sides and			0.01	m wide on the other two.				
This gives an active membrane area of				0.085	m wide by	0.052	metres.			
Membrane area =		4.42E-03	metres sq							
Membrane area required for output power										
Cell	*Power*	*Area of membrane*								
Voltage	*Density*	*required for output P*		Note: All we need here is the total power. The DC-DC converter						
Volts	*W/cm2*	*(cm2)*		will transform the output power to the desired 29.5 V able to supply 4.8 A.						
0.5	0.4	442.50		The DC-DC converter will also limit short circuit current and have						
0.6	0.36	491.67		thermal overload protection. DC-DC converters also have MTBF of						
0.7	0.175	1011.43		500,000 to 1,000,000 hrs.						
Cell	*Min No. of*			Length of fuel cell will equal the number of cells required plus 1 AND						
Voltage	*Cells*			1/5 and 1/7 of the total number for the humidifier cells. This is using						
Volts	*Required*			rule of thumb for humidification of a stack.						
0.5	10.01									
0.6	11.12									
0.7	22.88									
Cell	*Actual No.*		*No. of*		*Total No.*					
Voltage	*of Cell*		*Humidifier*		*of Plates*					
Volts	*Plates*		*Plates*		*in Stack*					
0.5	11		3.77		15					
0.6	12		4.11		17					
0.7	23		7.89		31					

FUEL CELL SIZE CALCULATION (cont'd)

Thickness of cell plates=			0.0025	metres
Thickness of End Plates (2 off)=			0.004	metres

Taking the length and width of the fuel cell and the height of the casing we calculate the volume left in the casing for the DC-DC converter.

Cell Voltage Volts	*Length of Fuel Cell Stack (m)*		*Volume Left in Casing for DC-DC Converter (m3)*	*(cm3)*
0.5	0.0455		8.38E-04	837.90
0.6	0.0505		8.04E-04	803.70
0.7	0.0855		5.64E-04	564.30

A review of DC-DC converter technology shows that encapsulated converters have long MTBFs and high transformed energy density. Figures quoted by Powerbox (a manufacturer) are 36 Watts /cubic inch which translates to 2.08W/cc. We use this figure to calculate the volume needed to fit the DC-DC converter and compare it to the available volume. We use the output power figure in the calculation, ie. the equivalent battery power.

DC-DC converter energy density =	2.08	W/cc
Volume required for DC-DC converter =	68.08	cc

Cell Voltage Volts	*Room for DC-DC Converter*		*Free Volume about Converter*	
0.5	YES		769.82	cc
0.6	YES		735.62	cc
0.7	YES		496.22	cc

WATER BALANCE CALCULATIONS									
Water needed for Humidification:									
Using the RMC equation for the partial pressure of water in 100% saturated gas. We have									
P(sat)=(377.4016-2.3147*T+0.003744*T^2)/14.696									
NB. This equation appears to be only good around 60C.									
Temp =	60	C=	333.15	K					
P(sat)=	0.20	ATM	This is the partial pressure of the moisture in the 100% saturated gas.						
P(sat)=	19854.28	Pa							
From Ballard results the H2 stream must be 50% saturated at the operating temperature									
and the air must be 100% saturated at the same temperature.									
The amount of water can be calculated from the ideal gas law: PV = nRT									
R=	8.3143	J/KM)	P=	1.99E+04	Pa				
T=	333.15	K	V=	0.001	m3 =	1	litres		
Moles of water/litre of gas(100% sat)=				0.007168	moles/litre				
Moles water needed for H2 at Max power =				0.012687	moles H2O/min in H2 flow at		50%	saturation	
Moles water needed for Air at Max Power =				0.063435	Moles H2O/min in Air flow at		100%	saturation	
HUMIDIFICATION REQUIREMENTS									
Total Moles of water needed at Max Power =					0.07612	moles H2O			
WATER PRODUCTION AT MAX POWER									
H2 gas flow at Maximum Power =				3.54	l/min =	0.00354	M3/min		
This gas flow is at a pressure of			1.01E+05	Pa and the temperature is			60	Centigrade.	
Moles of H2 at Max Power (from ideal gas law)=					0.129	moles/min H2			
Moles Air at Max Power (=5 times required O2 flow)=					0.323	moles/min AIR			
Moles of Water produced/min =			0.12908	moles/min					
CONCLUSION:									
	H2O production is		Greater	**than water requirement for humidification purposes.**					
	H2O production is		**1.70**	**times humidification needs.**					
	Excess Water produced =			3.71	moles =	122.44	gms of water/gas storage bottle		
					=	0.122	litres of water/gas storage bottle		

PRELIMINARY COSTING OF COMPONENTS												
							Retail			Density	Estimated	
ITEM							Price			Kg/cm3	Weight (Kg)	
12v DC FAN (40mmm*40mm*20mm) : FEC Electronics (287-970)							$30.00				0.090	
Guard for Fan: FEC Electronics							$5.48				0.005	
Particulate Filter for Fan: FEC Electronics							$0.20				0.001	
12 Volt Regulator for powering fan							$0.25				0.005	
Pressure Regulator (HP300) SS316, 10,000 psig from Indust Pyrometers							$848.00				0.400	Estimate
Nafion 117 @		$900	per m2 & considering the 0.5V/cell figures				$86.18			1.50E-03	0.007	
Pt for membrane assembly @			$618	per troy oz	0.12	mg/cm2	$2.11				1.64E-05	
			$19,869	per Kg	0.0012	Kg/m2						
Graphite plates at		$5	each	(ESTIMATED)			$75.00			2.00E-03	0.361	
Graphite and Teflon powder for printing membrane coating (Estimated)							$3.00				0.003	
End Plates (Fibre re-inforced plastic moulding) at				$5	each (ESTIMATED)		$10.00			1.50E-03	0.051	
Fibre glass bolts & nuts							$4.00				0.040	
Teflon piping and connectors							$20.00				0.020	
Pressure Bottle (based on approx price of Swaglok SS316 bottle)							$350.00				1.000	
FeTiMn Hydride at		$40	per Kg (estimate) &		5.60E+03	Kg/m3	$48.76				1.219	
Quick-fit type connector (Estimated on existing Swaglok mating connectors)							$70.00				0.050	
DC-DC converter (encapsulated and specifically designed for unit) (est.)							$250.00			3.00E-03	0.204	
Casing (plastic like existing NiCd battery casing)							$10.00				0.150	
Miscellaneous electrical, electronic and mechanical components							$100.00				0.100	
Assembly and Testing							$400.00					
						Total	$2,312.98			Total	3.706	Kg/unit
NOTE: the component costs are retail in most cases.												
Production component costs would probably be 1/3 the retail at least.												
Operating cost per bottle of H2 for unit @				$17.75	per m3	$4.38	per fill	OR	$6.34	per day		
LiSO2 battery which is single use and operates for 1 day costs;									$133.00	per day		
	This means that after approximately				18	*days use you break even.*						

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Batteries, Fuel cells, Fuel cell electrolytes, Radio equipment, Replacement, Hydrogen storage, Solid polymer electrolyte, Raven, Portable power source, Battery logistics, Battery costs, Fuel cell costs

20. ABSTRACT

A conceptual study has demonstrated the technical possibility of replacing the RAVEN radio batteries with a solid polymer electrolyte fuel cell. The fuel cell would operate on air and stored hydrogen released from a metal hydride. The study revealed that the fuel cell power source offered logistical benefits over nickel cadmium batteries and potential cost savings over lithium sulphur dioxide batteries. The study suggests that methods of chemically generating hydrogen and oxygen should be investigated as they may provide significant increased power and energy density for such fuel cell power systems.

Conceptual Study on Replacing the Raven Back Pack
Radio Batteries with a Solid Polymer Fuel Cell

Gregory A. Clark

(DSTO-TN-0014)

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